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Propulsion Instrument Electronics and Sensor Package

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Abstract

Spacecraft operators and designers need to understand the interaction between thrusters and spacecraft, and the limitations of ground test facilities make it important to validate models with data obtained from on-orbit conditions. Toward this end, a sensor package will be manifested aboard future spacecraft for the purpose of developing a predictive capability for how electric propulsion thrusters interact with typical spacecraft. A small Hall thruster and a micro-PPT will be operated in orbit and several instruments will characterize the environment induced by the thrusters. An ion probe will determine the energy and species distributions and a Langmuir probe will characterize the electron density and temperature of the back-flow region of the thruster plume. These data are intended for comparison with detailed numerical models in this region. Other instruments directly measure the effects of thruster operation on spacecraft thermal control surfaces, optical surfaces and solar arrays. Specifically, radiometric, photometric and solar-cell-based sensors are under development.

Introduction

This paper describes the status of a spacecraft sensor package, including initial design and experimental results, intended for the purpose of collecting data while on-orbit. This data will be used to validate models currently under development.

A critical part of the spacecraft sensor package is the characterization of interactions between the on-board thrusters and the spacecraft. These are significant because electric thrusters' exhaust products can be highly energetic, generating erosion and secondary deposition products wherever plume impingement occurs. In addition, wear materials are emitted from the thruster and flow through the plume to deposit on spacecraft surfaces. These effects can lead to degradation in optical surface properties, solar array performance, and radiator thermal properties. Several ground-based measurements have been made to assess these effects,¹⁻³ but the chamber effects dominate the measured signals in the back-flow region.

In response to this need, a collaborative program between AFRL and JPL was established to determine the spacecraft interactions with a Hall thruster and MicroPPT. This goal will be accomplished using an on-board diagnostics suite, coupled with ground tests, flight measurements using ground-based remote sensors, and a modeling effort by which extrapolations can be made to future system configurations. Figure 1 and Figure 2 show the current designs of the Hall thruster and MicroPPT respectively.

Instrument Description

Based on the experiences from the Electric Propulsion Space Experiment (ESEX) mission,⁴ a philosophy was developed for the appropriate measurement of effects on a host spacecraft from thruster operations. This includes several key points: maximize the number of measurements that can be conducted from remote observations (because they have a minimal impact on spacecraft design); perform direct measurements of both critical engineering parameters (for example, thruster effects on optical surfaces) as well as thruster parameters (plume ion flux, for example); and finally, design the instrumentation so that the data are expected, from pre-flight analysis or test, to show a simple, trendable signal that characterizes the effect in question. Furthermore, the use of modeling and simulation throughout the program is key to describing the effects of these devices on generic spacecraft, as well as planning the logistics of the sensor design. Determining the location of the sensors on the spacecraft, for instance, can be aided dramatically even by first-order calculations of the plume flowfield and how it strikes other spacecraft surfaces.

Based on the above criteria, a set of measurements was identified very early in the program. These measurements focused on three classes of data: (1) direct engineering measurements of the contamination impact to the host spacecraft from the thrusters including thermal and optical surface degradation, and effects on thin film solar arrays;

(2) plume characteristics to supply required modeling input data including electron and ion species in the exit plane and the plume; and (3) thruster performance data such as thrust, specific impulse (ISP), and efficiency. To address these measurement requirements, a suite of on-board sensors were baselined including: an ion probe, two electron sensors, a pair of solar cells, ten radiometers, and ten photometers. Further ground-based tests such as communication tests,⁵ or optical spectroscopy⁶ may also be utilized.

Figure 3 shows the current layout of the sensors on a spacecraft propulsion panel, and their location relative to several of the external components of the remainder of the propulsion subsystem. Not shown are the Hall thruster internal components, which include the xenon flow system and the power processor, the interface electronics unit for the onboard sensors, or the photometers, radiometers, and solar cells. These smaller sensors (each is expected to have about 1cm² area) will be distributed around the propulsion panel and spacecraft zenith deck in coordination with the detailed spacecraft design, which is in progress.

The interface between the sensor suite and the spacecraft is managed by the Propulsion Sensors Interface Electronics (PIE) unit. The PIE inputs are the 28 V spacecraft power and an RS-422 digital interface for commands and telemetry. The PIE, designed and built by Broad Reach Engineering (BRE), provides the proper voltages and currents to drive the individual sensors, contains the signal processing and multiplexing circuits, and is responsible for the software interface for the sensors' command decoding and telemetry processing.

Finally, the critical design criteria for the sensors were mass and cost. The Propulsion Sensors element of the spacecraft, including the sensors, the PIE, and the harness, fasteners, etc., carries a design limit of 1.5 kg. Furthermore, the development process is designed to minimize system cost by accepting risk consistent with USAF class D space experiments, which are characterized by a proto-qualification testing approach, a single-string design, and limited parts selection. The following paragraphs describe each of the sensors types, provide a description of where they are located and the corresponding rationale, and describe the current status of each.

Contamination Measurements

The contamination measurements are loosely based on experience from the ESEX contamination data.⁷ For ESEX, these measurements consisted of radiometers, thermoelectrically-cooled quartz crystal microbalances (TQCMs), and a solar array segment. Based on the mass and power constraints, radiometric sensors and solar cells were selected for the space package. In addition, a photometer was added to address optical surface degradation. Each of these three sensors uses the sun as a relatively constant source, against which changes due to thruster operation are measured. All of the contamination sensors will be placed on sun-facing surfaces on the spacecraft in order to maximize their insolation exposure throughout the mission. These surfaces include the

zenith deck itself, as well as on a 'billboard' panel facing both the sun and the thruster placed diagonally on the propulsion panel.

Radiometers

The radiometers are used to measure the effect of the thruster on the thermal properties of typical spacecraft surfaces. The basic design consists of a thin plate whose exposed surface is treated with a typical spacecraft material such as Kapton, thermal paint, or a radiator surface like silvered Teflon. The plate is thermally isolated from the spacecraft, such that the plate's temperature is strongly affected by the treatment's thermal properties. The temperatures of the surface and the spacecraft below are measured and recorded as a function of the solar illumination. As the surface material degrades from thruster operation, the emissivity and absorptivity of the material changes, and the temperature profile changes accordingly. Figure 4 shows a representation of this generic design.

Using this device to measure thruster effects depends on a thorough understanding of the nominal performance of the material in the orbit environment. For materials such as S13-GLO white paint or silvered Teflon, the normal degradation from effects such as atomic oxygen is well characterized, so these materials make good candidates for these sensors. Because of the requirements for small dimensions, the temperature sensors themselves must also be relatively small in size. The current designs focus on the use of the Analog Devices AD590 temperature transducer. This device is flight qualified and will be used extensively elsewhere on the spacecraft. The AD590 sensors have well-characterized behavior over the expected temperature range, and have a convenient calibration curve of 1 micro-A per degree Kelvin. The radiometer design will be based on the same premise as the generic description above, but may include a more advanced designed to take advantage of weight savings. For example, the current design uses a bare AD590 die bonded to the sensor plate in order to reduce the plate's overall heat capacity. The AD590 die's mass is approximately 2 mg, which is small compared to the plate's mass of approximately 300 mg.

Solar Cells

The solar cell design can also be traced to the ESEX program. In this measurement, the voltage and current characteristics of the array are measured over the life of the mission to determine the performance degradation as a result of reduced surface transmission induced by thruster operation. For ESEX, only two points were measured for the array performance – the open circuit voltage and the short circuit current. For TechSat 21, data will be acquired over the entire I-V curve through a series of switchable load resistors.

Selection of the cell technology to be tested involves a trade between older, better-understood technologies such as silicon cells, and more advanced technologies likely to be used on more technologically aggressive missions. The USAF research community is

enthusiastic about spacecraft use of thin-film solar array technology. Figure 5, for instance, shows the thin-film technology that is baselined for the main array on spacecraft. The thin-film arrays do not, however, have significant data on how they nominally perform on-orbit – making definitive statements about the Hall thruster impacts more difficult.

The ultimate selection for the array to be flown as a part of the spacecraft sensor suite has not been made. Aside from the debate on silicon-based vs. thin-film technology, there is a secondary debate on what thin-film technology is most appropriate for this application. Further complications include limits on the amount of current output from the array segments to the PIE, predictions of expected on-orbit performance, and temperature effects on the array output.

Photometers

The final part of the contamination measurements suite is the photometers. These devices will be used to assess the impact of the Hall thruster on optical surfaces and coatings. The design features a PIN photodiode collector that receives incident sunlight behind a silica window which carries the optical coating of interest. Optical coatings under consideration include first surface reflectors, dielectric mirrors and filters, and anti-reflective coatings. Measuring the change in the collected sunlight as the mission progresses enables an assessment of the thruster impacts. Figure 6 shows an example of a photometer under consideration for this application.

The photometers are relatively low-risk items since there are numerous space-qualified applications already, such as sun sensors. The photometers will be sized according to the mass constraints of the sensor system, while ensuring that the widest range of data is acquired.

Plume Characterization Measurements

There are two primary motivations for these measurements: (1) to provide inputs and verification for current and future modeling efforts of Hall thrusters' interactions with spacecraft; and (2) to understand the Hall thruster plume characteristics in the space environment. As such, the instruments selected will measure the mass and energy distribution of xenon ions, the electron density and temperature in the near-field region of the thruster, and assess the current return path from the plume and ambient space plasma to the spacecraft. All of these sensors are currently in development and represent a significant part of the program effort.

Ion Probe

The ion probe being developed for a spacecraft flight will measure the mass and energy distribution of ions emitted from the thruster during operation. The primary ions of interest include Xe^+ , and Xe^{++} , but may also include others as the design modeling effort matures. Figure 7 shows the critical components of the current prototype: ions pass through a pair of nested hemispherical section shells for energy selection, followed by a yoked NdFeB permanent magnet for mass separation. Not shown are ion lenses to be located at the input of the hemispherical section and between the energy and mass sections. Also not shown is a microchannel plate detector, which is expected to be required due to the low ion currents in the back-flow region.

Studies on the effectiveness of the current design have shown promising results; however, the interface between the instrument and the PIE remains a critical design issue. The expected current range, for instance, could be less than 1 nanoamp even after the 1000X amplification achieved by the microchannel plate. Other interface issues include shielding against stray electromagnetic emissions while maintaining the required level of sensitivity, and providing a complex system of voltage supplies and measurements with low mass.

Measuring the low currents while maintaining an acceptable signal-to-noise ratio appears to be the greatest challenge to date. To address this issue up front, a breadboard of the current sense circuitry was built and tested by BRE. This breadboard was successful in measuring current levels down to 1 nanoamp with a resolution of a 0.25 pico-amp, with relatively little noise on the telemetry. With this success in hand, the majority of future work for the ion probe will focus on validating its functionality: first with a calibrated ion beam, followed by an integrated firing with the thruster itself. Pending experiments will also more clearly identify the range of the expected current, enabling the flight design to be finalized.

Electron Probes

The electron probes are based on traditional Langmuir probe operation where the probe is biased with either a positive or negative voltage, and the collected current is recorded. For a spacecraft application, there are two probes – one mounted on a fixed boom off of the propulsion panel (see Figure 3), and the second mounted on the zenith deck. Both designs will have a voltage sweep range of +50V to -50V, and will be capable of measuring currents as high as 1 mA at 12 bit resolution. Both probes will be oriented into the RAM direction for at least 30 seconds per orbit (although the zenith deck probe will be in the RAM for much longer) in order to assess the ambient environment.

The boom mounted probe will be used to determine the electron temperature and density in the near-field region of the thruster plume. This sensor is a 5cm diameter conducting sphere, mounted 25cm from the propulsion panel. Designs under consideration for mounting include a simple, fixed boom constructed of a composite tube to minimize weight, as well as a smaller boom mounted from the 'billboard' on the propulsion panel.

The primary purpose of the zenith deck probe will be used to determine the current return from the plasma environment. This probe is a 5 cm conducting disk which is electrically isolated and mounted directly to the spacecraft structure.

The instrumentation design schedule puts the detailed design of the two electron probes later in the process, because the sensors are relatively simple. The electron sensor is expected to be validated primarily against the Hall thruster, although other plasma sources may also be used as available.

Performance Measurements

The final part of the on-board diagnostics will be used to measure the performance of the thrusters. The sensors to be used for these measurements are primarily those already included in the spacecraft ADCS. The ESEX performance measurements showed that the complications added by using an on-board accelerometer, for example, can be avoided by using existing means to measure thruster performance.¹¹ The other measurements required for the thruster performance evaluation, such as flow rate, power input, etc. are all being measured by the operating telemetry within the system. The most recent ground measurements of thruster performance showed a thrust of 12.5 mN, an ISP of 1,240 sec, and an anode efficiency of over 41%. On-orbit performance is expected to be the same.

Future Sensor Work

In general, the focus is shifting from developmental testing to the Engineering Model hardware design, fabrication, and test. The sensors will each be tested for functionality first, followed by an interface verification with the engineering model PIE, and finally tests with the thruster to validate their response. Updates to the flight designs will then be incorporated at the critical design review, and flight hardware fabrication will be initiated. Typical flight qualification testing of the three assemblies will be conducted at the component level, including vibration, thermal cycling, and thermal vacuum. Once the qualification tests are complete, all of the flight hardware will be delivered to TRW for the final integration with the rest of the propulsion subsystem components on the panel. Delivery of the three fully assembled flight panels to the spacecraft integration contractor, MicroSat Systems, Inc., is scheduled in mid-2003.

Conclusions

The propulsion subsystem development effort is a challenging project designed to push technology towards advanced microsatellite applications, while maintaining cost and schedule constraints. A critical part of this effort is the measurement of the interactions between the thruster and the spacecraft, which will be accomplished by a suite of advanced, miniaturized sensors. The on-board sensors development is closely coupled

with a ground test and modeling program to be able to produce an integration handbook for future Hall thruster systems. Development tests for all of the sensors and the PIE is ongoing, and preliminary tests show promising results for all of the technical challenges.

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Figures

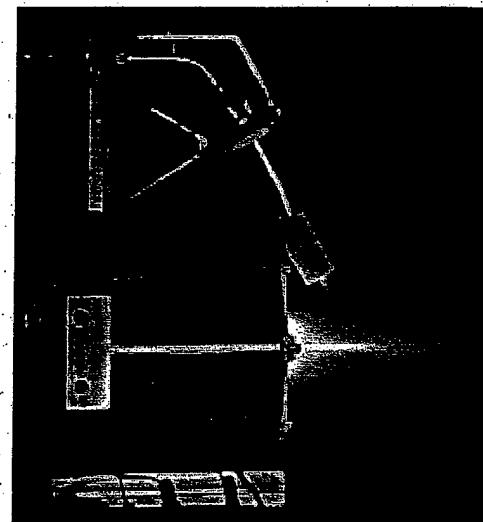


Figure 1 – Hall Thruster and Cathode

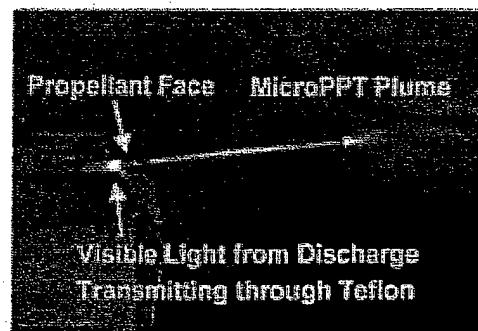


Figure 2 – MicroPPT

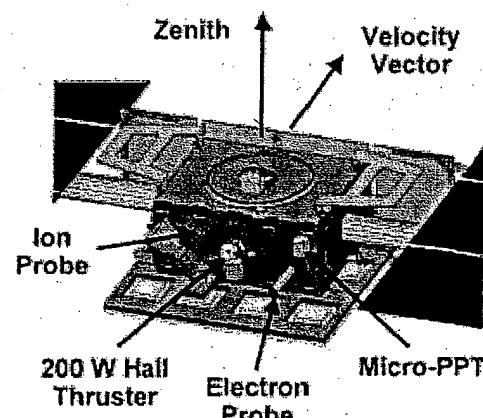


Figure 3 – Layout of the Propulsion Subsystem

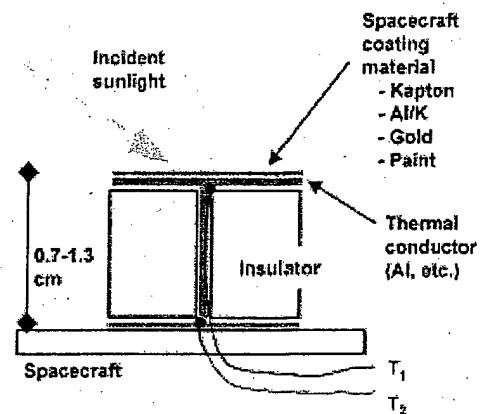


Figure 4 – Generic Radiometer Design for Contamination Measurements

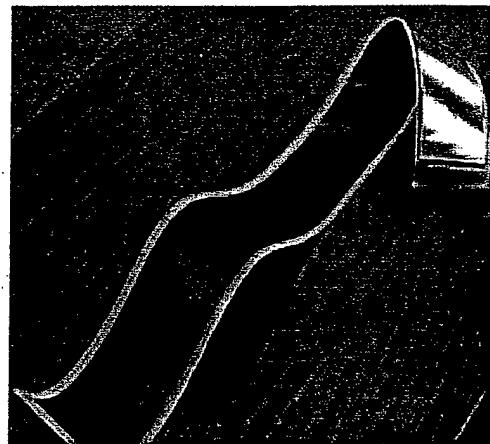


Figure 5 – Thin-Film Solar Array Technology Similar to that used on the main array

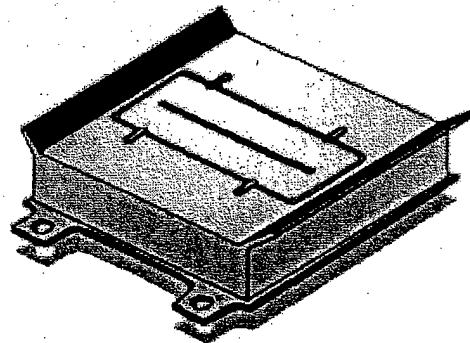


Figure 6 – Example of Photometer to be Used for Contamination Measurements

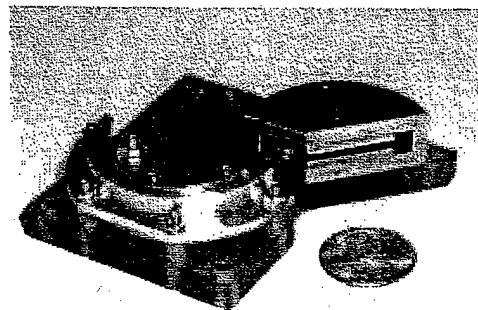


Figure 7 – Prototype of the Ion Probe

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